QUANTITATIVE METHODS FOR RESERVOIR CHARACTERIZATION AND IMPROVED RECOVERY: APPLICATION TO HEAVY OIL SANDS

ANNUAL REPORT

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Abstract

Improved prediction of interwell reservoir heterogeneity is needed to increase productivity and to reduce recovery cost for California's heavy oil sands, which contain approximately 2.3 billion barrels of remaining reserves in the Temblor Formation and in other formations of the San Joaquin Valley. This investigation involves application of advanced analytical property-distribution methods conditioned to continuous outcrop control for improved reservoir characterization and simulation. The proposed investigation is being performed in collaboration with Chevron Production Company U.S.A. as an industrial partner, and incorporates data from the Temblor Formation in Chevron's West Coalinga Field.

Efforts during the past twelve months have focused on developing three-dimensional geologic models for reservoir characterization, incorporating permeabilities into the models, and then using the models for reservoir simulation. In conjunction with this work, five facies tracts have been identified in the Temblor Formation using cores and outcrops: incised valley, estuarine, tide- to wave-dominated shoreline, diatomite, and subtidal. Three-dimensional facies tract and facies group models have been constructed for two areas within West Coalinga Field.

Additional work during the past year includes further investigation of the applications of the new drill-hole minipermeameter probe. The theory for analyzing radial gas flow from a cylindrical borehole into the surrounding medium has been expanded to include possible variations in system geometry. In addition, the physical basis for a spatial weighting function has been developed using streamline coordinates. The results are very encouraging for adapting the new probe design to various field situations.

Permeability data collected from outcrop near Escalante, Utah, support a new concept for representing natural heterogeneity, which is called the *facies-fractal* concept [Lu et al., 2001]. We anticipate that applying the facies-fractal concept to the sedimentary structure at West Coalinga Field will be the main basis for simulating the oil recovery process. The simulation will be fully developed during the final project period.

T2VOC, which is a numerical flow simulator capable of modeling multiphase, multi-component, non-isothermal flow, is being used to model steam injection and oil production for a portion of section 36D in West Coalinga Field. This simulator has been used extensively by government agencies and private corporations to model the flow of water, air (steam), and oil in multi-dimensional, heterogeneous porous media.

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Results and Discussion

Geological Characterization

During the past twelve months, object-based, three-dimensional geologic models were constructed for parts of sections 31A and 36D in West Coalinga Field (Fig. 1). These models are being used for the incorporation of permeability distributions for application to steam-flood simulation. The models incorporate geophysical logs as well as lithologic data and depositional interpretations from our core and outcrop investigation of the Temblor Formation in the Coalinga area. Specific geologic models produced include facies tract and lithofacies group models. Multiple realizations of both types of models were generated to represent the geometry of reservoir zones. In addition, a statistical analysis involving approximately 2000 data points from 13 cored wells in West Coalinga Field was conducted to identify groupings of lithofacies and to evaluate permeability trends in both lithofacies and facies tracts. A cluster analysis was performed to group lithofacies based on permeability, porosity, sorting, grain size, and percent sand. GOCAD three-dimensional modeling and visualization software is being used for this investigation.
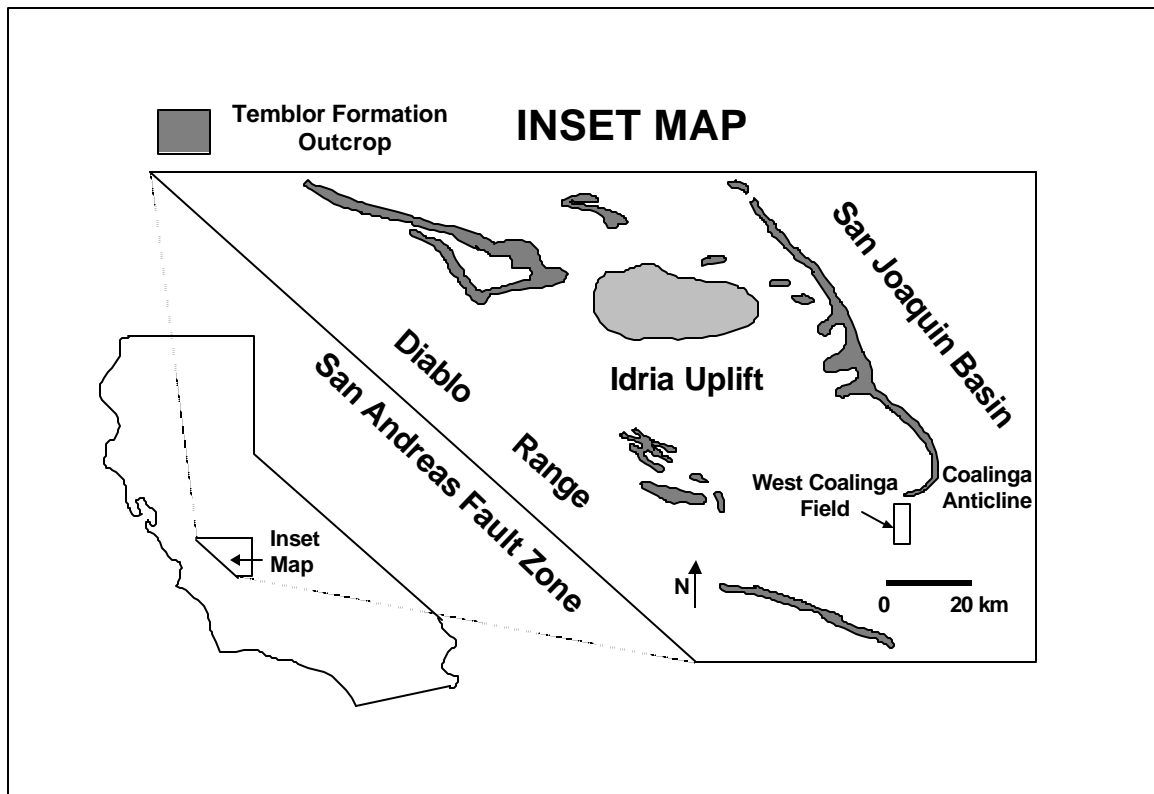

Figure 1. Location map of the Coalinga area, California

Some of the steps followed for constructing the three-dimensional geologic models of facies tracts and lithofacies groups were:

1) Loaded bounding surface horizons to provide structural constraints;
2) Loaded continuous and discrete geophysical log, lithofacies group, and facies tract data;
3) Developed model architecture and geologic regions to define the facies tract and lithofacies group stratigraphic grids;
4) Applied sequential indicator simulations to develop a representative and geologically reasonable lithofacies group model; and
5) Examined the facies tract and lithofacies group models for geological validity and compared modeling results with cores and geophysical logs.

For the facies tract models, reference horizons were defined based on regional sedimentological and sequence-stratigraphic relationships. These horizons were identified in cores and outcrops as stratigraphic bounding surfaces that separate five major facies tracts: incised valley, estuarine, tide- to wave-dominated shoreline, diatomite, and subtidal. This approach provides a structural constraint by forcing the model grid to conform to the surfaces, including honoring truncation of stratigraphic intervals by unconformities. In section 31A, six bounding surfaces with a region between each surface were created in GOCAD to represent the five facies tracts present in the northern part of West Coalinga Field. In Section 36D, which is located in the southern part of the field, four bounding surfaces and three regions are present. The facies tracts present in the southern part of the field are estuarine, tide- to wave-dominated shoreline, and subtidal.

Results from integrating geologic facies with the outcrop permeability data obtained from our field site near Escalante, Utah, were presented at the annual national meeting of the Geological Society of America [Lorinovich et al., 2000]. A paper on the reservoir characterization of Coalinga field, including construction of the geological models, was presented at the American Association of Petroleum Geologists annual national meeting [Bridges and Castle, 2001].

Permeability Measurement

Progress continued on application of the drill-hole minipermeameter probe, which was developed under this project. Using the new probe, field permeability measurements were recorded in triplicate at approximately 500 points on outcrops near Escalante, Utah. The theory for analyzing radial gas flow from a cylindrical drillhole into the surrounding medium has been expanded to include possible variations in system geometry. The variations tested to date include thickness of the packer (or seal), depth of the drillhole into the outcrop, and radius of the drillhole. There is a geometric factor for each variation of the probe/rock system, which accounts for the system geometry and the diverging flow through the porous media domain. In order to determine the geometric factor for different system geometries, finite-difference computer simulations were developed to model the pressure-distribution throughout each system. A paper on the development of the new drill-hole probe was presented at the Geological Society of America fall meeting [Dinwiddie et al., 2000[a]]. The data resulting from field application of the new drillhole probe were presented at the fall meeting of the American Geophysical Union [Dinwiddie et al., 2000[b]]. A similar paper,

which covered both the development of the new probe and the resulting data, was presented at the American Association of Petroleum Geologists annual national meeting [Dinwiddie et al., 2001].

The physical basis for a spatial weighting function has been developed utilizing streamline coordinates [Molz et al., 2001]. Applications of the spatial weighting functions are presented for the conventional surface probe and the new drill-hole probe. Spatial weighting function distributions indicate that with diverging flow-field instruments, such as the gas minipermeameter, porous medium volumes in the inlet vicinity are heavily weighted, with volumes near the seal boundaries shown to be extremely important. The technique described allows one to quantify the size and shape of the sub-volume of a domain contributing to an effective permeability measurement. A paper elucidating this subject matter was presented at the fall meeting of the American Geophysical Union [Molz et al., 2000]. Additionally, a comment has been prepared on a recently published paper [Tartakovsky, et al. 2000]; this comment has been submitted to *Water Resources Research*, and it should clarify some misconceptions and misnomers raised by Tartakovsky and his colleagues, by invoking knowledge gained through spatial weighting function concepts [Molz and Dinwiddie, 2001].

Fractal Analysis

In addition to the mini-permeameter and field permeability work described above, core data, primarily permeability, from the Coalinga Oil Field (Temblor Formation) was analyzed for fractal properties and structure. This was a difficult task because of the lack of quantity and continuity of data. Variance scaling is definitely present in the data, but the associated Hurst (H) coefficient was difficult to calculate. Using spectral techniques, a value in the vicinity of 0.3 was estimated. Further analysis of the core data, which included a series of facies tracts, yielded sets of Log(k) increments that were not Gaussian. This differed from our Utah data, which were obtained within what we are calling pure facies. This difference is explained in a manuscript that is currently in review [Lu et al., 2001]. The approach outlined in the manuscript is being applied to the simulation of steam flooding in section 36D of West Coalinga Field. Three-dimensional realizations of intrinsic permeability distributions have been generated at an appropriate grid scale.

A new concept for representing natural heterogeneity was developed in a related project. It is called the *facies-fractal* concept [Lu et al., 2001]. Data from the Escalante outcrop support this concept, so it is being used to simulate oil recovery in the Coalinga Field. Motivation for the concept as applied to the Coalinga data is given below.

Permeability may be conceived as exhibiting two components of variation: a "structure" or "systematic" component and a "random" or "noise" component. If the facies concept is introduced, then the "structure" may be associated with the facies, and the "random" component associated with the permeability variation within facies.

Previous studies have presented evidence that log(k) increments (k = intrinsic permeability) within pure facies often follow a Gaussian distribution. For example, a k data set from a vertical Berea sandstone core was obtained in the laboratory using a surface gas mini-permeameter (Fig. 2). It
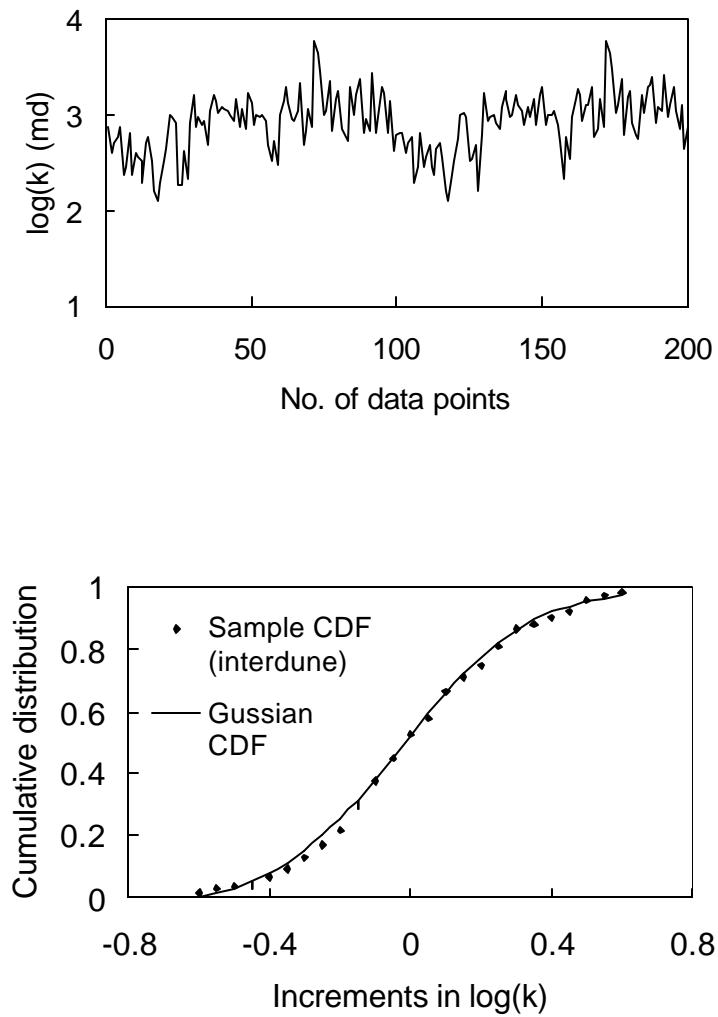
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Figure 2. *Top:* Permeability data collected from the inter-dune facies in eolian sandstone. *Bottom:* The cumulative distribution of the increments of log(k) showing that the log(k) increment distribution is highly Gaussian.

consists of 2,884 consecutive k measurements with half-inch (1.27-cm) spacings. Recently, Lu and Molz [2001] concluded that both the k increments and log(K) increments have non-Gaussian distributions with heavy, non-Gaussian tails when the entire data set is used for the analysis. However, under the assumption that permeability is related to at least three of the primary facies types found in eolian sequences (that is, grain-flow, wind-ripple, and inter-dune), Goggin [1988] provided evidence that k in each facies is log-normally distributed. Therefore, the log(k) increments for each stratification should be approximately normally distributed. We checked for this behavior using Goggin's [1988] data. Shown in Figure 2 are results for the inter-dune data, indicating that the cumulative distribution of log(k) increments are well approximated by a Gaussian cumulative distribution function. Rescaled range (R/S) analysis of log(k) also shows that long range correlated log(k) structure is found with a Hurst coefficient H = 0.39 (Fig. 3). Similar results were obtained for the grain-flow and wind-ripple facies.
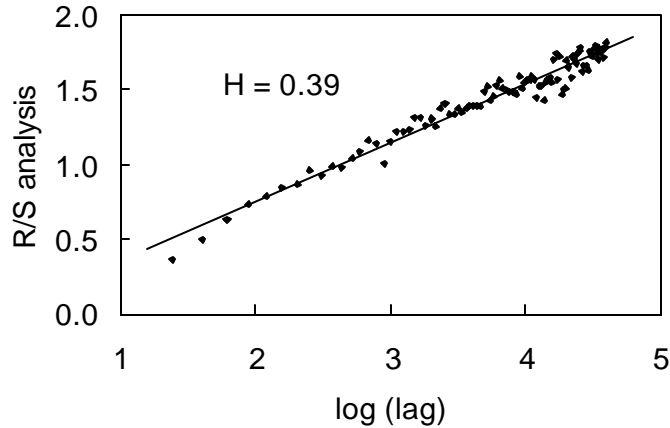

Figure 3. Rescaled range analysis of log(k) collected from the inter-dune facies in eolian sandstone. The Hurst coefficient, H, is given by the slope of the best fitting straight line.

As part of our current project, field k measurements were made by the present authors using the newly designed drill-hole, gas, mini-permeameter, described previously, with a 15 cm measurement spacing on a 6 × 21 m sandstone outcrop near Escalante, Utah [Dinwiddie et al., 2000[a,b]; Lorinovich et al., 2000; Lu et al., 2001]. About 500 k measurements were collected along three horizontal transects and four vertical profiles. Among them, two horizontal transects with 269 measurements are located in a bioturbated, shallow-marine sandstone that is considered as a single, pure facies. While the data are still undergoing final analyses, the log(k) increments have a Hurst coefficient of 0.34 and are highly Gaussian as documented in Figure 4. We conclude, therefore, that there is field evidence for Gaussian behavior of log(k) or log(K) increments within pure facies. This is one of the main motivations for proposing the fractal/facies model.
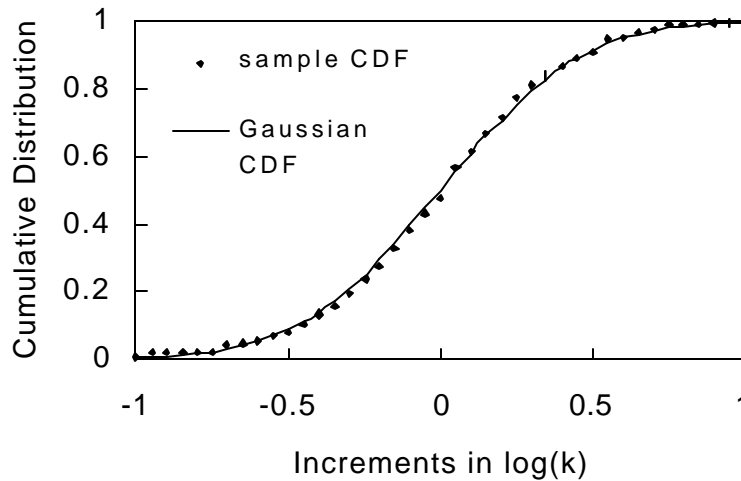
Figure 4. The cumulative distribution function for the log(k) increments of a bioturbated marine sandstone facies in Southern Utah. The distribution function is highly Gaussian.

Reservoir Simulation

The numerical flow simulator that is being used to model the injection of steam and production of oil is T2VOC [Falta et al., 1995]. T2VOC, which was developed by USDOE at the Lawrence Berkeley Laboratory, is capable of modeling multiphase, multi-component, non-isothermal flow. This simulator has been used extensively by government agencies and private corporations to model the flow of water, air (steam), and oil in multi-dimensional, heterogeneous porous media.

Reservoir simulations are being performed using three different means of distributing permeability for a portion of section 36D: facies tract, facies group, and fractal group. Oil saturations, which were derived from core analysis and provided by Chevron, have been integrated into the flow simulator.

The geologic model grids and their associated properties created in GOCAD were imported into the numerical flow simulator (T2VOC). The importation of the model grid into the flow simulator required a substantial effort in computer code development and programming. This involved converting the GOCAD geological model grid, which was composed of 33 surfaces that modeled the stratigraphic architecture, into a regular grid composed of 9600 cells. The grid consists of 10 cells in the x direction (Easting), 30 cells in the y direction (Northing), and 32 layers (32 cells in the z direction). From the coordinates of the vertices

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provided by the geological model, the following model inputs for T2VOC were calculated for each cell:

1) Centroid Coordinate
2) Cell Volume
3) Distance from centroid to cell interface (for all eight interfaces)
4) Cell Interface Area (for all eight interfaces)
5) Cosine of the angle of the gravitational vector between centroids (in all eight directions).

In addition, the oil saturation and permeability associated with each of the vertices was used to calculate an average oil saturation and permeability for each grid cell. The fractal permeabilities, which are based on the facies group model, were imported separately and assigned to the appropriate cell. The bottom layer and top 3 layers have very low permeabilities assigned to them (1e-16 m^2), so that they essentially form no flow boundaries.

Steam injection rates, water production rates, and well construction details were provided by Chevron. It was necessary to modify the injection rates due to the 5-Spot configuration, as the assumption is that the edge of the model is a no-flow boundary. In a 5-Spot injection pattern, it is assumed that the corner wells (such as A and C in Figure 5) are contributing one-quarter of their injection volume into the modeled area. In the case of adjacent 5-Spot patterns, the injectors that share a corner (such as B in Figure 5) contribute only half of their injection volume into the model area. For a given well, the overall rate is divided up among the elements that correspond to the perforated zones, and the injection rate is prorated to the permeability of the element. This condition avoids the numerical problem of injecting at a high rate into a low permeability layer.
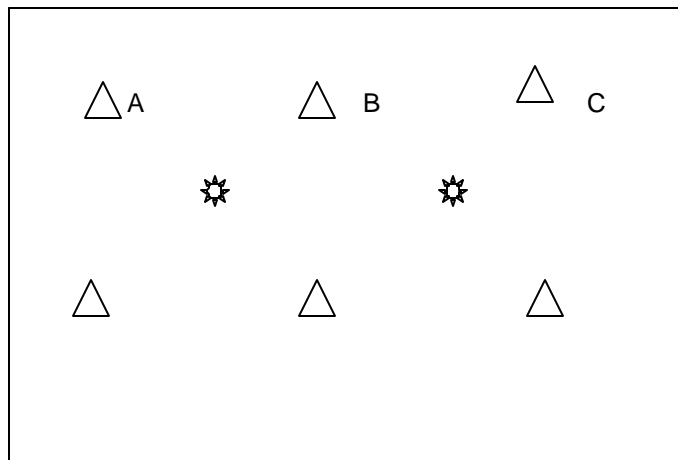
Figure 5. An adjacent 5-Spot configuration with injectors as triangles and producers as circles.

Initial comparisons of field production with simulated production reveals that some of the initial estimations

of reservoir properties will need to be adjusted. Discussions with Chevron identified the following parameters that could be adjusted to obtain a better fit:

1) Initial reservoir pressure
2) Initial oil saturation
3) Relative permeability coefficients
4) Vertical anisotropy.

Simulations are currently underway to determine which of these parameters is the most sensitive and has the greatest influence on the production values.

Conclusions

Continued investigation of applications for the new drill-hole minipermeameter probe is providing results that are very encouraging. The theory for analyzing radial gas flow from a cylindrical borehole into the surrounding medium has been expanded to include possible variations in system geometry, and the physical basis for a spatial weighting function has been developed using streamline coordinates.

Three-dimensional geologic models have been constructed using data and interpretations from cores and outcrops. Preliminary simulations of the three different geologic models, facies tract, facies group, and fractal group, are underway. Initial comparisons of field production with simulated production reveals that some of the initial estimations of reservoir properties will require adjustment.

We anticipate that applying the facies-fractal concept to the sedimentary structure at the Coalinga field will be the main basis for simulating the oil recovery process. Fully developing the simulation and completing several manuscripts describing overall project results will form the bulk of our work during the final project period.

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